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A model-based evaluation of post-fire fuels management approaches to mitigating future wildfire severity in dry coniferous forests

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ABSTRACT

Background. High-severity fires leave behind a pulse of dead trees that contribute to fuel accumulation over time. Prescribed fire and logging fire-killed trees can reduce surface woody fuels after fire, but their effects on subsequent wildfire effects are not well understood. **Aims.** This study examined the potential for post-fire logging and prescribed burning to manage post-fire fuels and mitigate future wildfire effects. **Methods.** We used surface woody fuel surveys from high severity patches within 68 wildfires (1970–2007) to model post-fire logging effects on fuel consumption and fire effects in simulated wildfires and prescribed fires. **Key results.** Post-fire logging reduced simulated wildfire intensity and severity starting 5–10 years after the initial wildfire. Prescribed burning reduced small diameter woody fuels considerably but effects on large woody fuels were often minimal. **Conclusions.** Post-fire logging and prescribed fire are complementary approaches for managing post-fire fuels: logging reduced large-diameter woody fuel loads while prescribed fire primarily reduced fine fuels. **Implications.** The combination of post-fire logging and prescribed fire can be effective management approaches for reducing surface woody fuels and potential future wildfire severity, the most appropriate approach is likely to vary based on conditions after the initial high-severity wildfire, anticipated fuel accumulation and management objectives.

Keywords: fire effects, forest management, fuels, fuel dynamics, mixed-conifer forest, post-fire logging, prescribed fire, reburn, severity, wildfire.

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Introduction

Wildfires can alter the severity of subsequent wildfires ('reburns') by consuming existing forest fuels and initiating a process of post-fire fuel succession driven by decomposition of fire-killed trees and growth of recovering vegetation (Agee and Skinner 2005; Prichard *et al.* 2017; Cansler *et al.* 2022). Low severity fires can reduce future wildfire intensity and severity by consuming a high proportion of surface fuels while limiting mortality of trees and large shrubs (Harvey *et al.* 2016; Cansler *et al.* 2022). In contrast, wildfires that burn with substantial high severity effects can increase future wildfire severity by killing large proportions of trees and creating a source of new surface fuels as the dead trees decompose and deposit litter and woody fuels on the forest floor (Ritchie *et al.* 2013; Coppoletta *et al.* 2016; Lydersen *et al.* 2019; Peterson *et al.* 2023*a*). Therefore, reducing surface fuel loads and maintaining them at levels that allow wildfires to burn without killing high proportions of overstory trees is an important objective in restoring low-severity fire regimes in dry coniferous forests of western North America (Agee and Skinner 2005; Franklin and Johnson 2012).

Dry coniferous forests of western North America have experienced a substantial increase in the frequency and extent of high severity wildfires in recent decades (Abatzoglou and Williams 2016; Parks and Abatzoglou 2020). Forest management practices such as fire exclusion and livestock grazing have contributed to these changes by promoting higher stand densities, greater abundance of fire-sensitive tree species, forest health problems and higher surface fuel loads (Hessburg and Agee 2005; Abatzoglou *et al.* 2018). Earlier snowmelt and warmer, drier summers also contribute to increasing mean annual area burned and higher burn severity by lengthening fire seasons and increasing the frequency of severe fire weather (Abatzoglou and Williams 2016; Westerling 2016; Parks and Abatzoglou 2020; Ellis *et al.* 2022).

After high severity wildfire, the potential intensity and severity of a subsequent reburn changes through time as disturbance-generated fuels accumulate and decay and as post-fire vegetation develops fire resistance (Parks *et al.* 2014; Coppoletta *et al.* 2016; Harvey *et al.* 2016; Lydersen *et al.* 2019). Wildfires that had substantial high severity effects create pulses of standing dead trees that decompose over time, depositing foliage, branches, tops and boles on the forest floor where they serve as woody fuels for one to several decades (Ritchie *et al.* 2013; Dunn and Bailey 2015; Peterson *et al.* 2023*a*). Surface woody fuels often reach peak loadings within 10–20 years after wildfire in dry coniferous forests as rates of fuel deposition from snag decomposition decline and losses of woody fuels to wood decay processes increase (Hall *et al.* 2006; Dunn and Bailey 2015; Peterson *et al.* 2023*a*). Wood decay processes also alter woody fuel properties such as surface-area-to-volume ratios (SAV) and moisture retention that influence ignition, fire behavior and fuel consumption during fire (Brown 2003; Hyde *et al.* 2011). As a result of these deposition and decay processes, reburns occurring within 5–10 years of the prior fire often burn with low intensity and severity in dry coniferous forests, as they burn primarily litter and fine fuels (Collins *et al.* 2009; Donato *et al.* 2013; Parks *et al.* 2014, 2015). Reburns occurring after a decade or more can be more severe owing to greater amounts of available fuels that generate greater heat release, longer fire residence times, higher vegetation mortality rates and more soil heating (DeBano *et al.* 1998; Brown 2003; Parks *et al.* 2014).

Post-fire fuels management – post-fire logging, prescribed burning, or both – may help mitigate the potential for high severity effects within reburns by reducing forest fuel loads at different stages of post-fire snag decomposition and woody fuel accumulation (Ritchie *et al.* 2013, Peterson *et al.* 2015, Coppoletta *et al.* 2016, Nemens *et al.* 2019). Post-fire logging can reduce maximum woody fuel accumulations after high severity wildfire (Ritchie *et al.* 2013; Peterson *et al.* 2015), despite an initial increase in woody fuel loads from logging slash (Peterson *et al.* 2015; Johnson *et al.* 2020; Kennedy *et al.* 2024); however, the impact of post-fire fuel reductions on subsequent fire behavior and effects is not well understood. Prescribed burning is typically effective for reducing and managing surface woody fuels in mature forests (Vaillant *et al.* 2009; Stephens *et al.* 2012; van Mantgem *et al.* 2016); however, its effectiveness for managing post-fire fuel dynamics and high fuel loadings following high severity wildfire is still not well established.

In this study, we used a fire effects model to simulate the effects of post-fire logging and time since wildfire on fuel consumption and fire severity under two fire weather and fuel moisture scenarios, corresponding to summer wildfires and early season (spring) prescribed fires. We focused on high severity burn patches within large wildfires that burned with predominantly mixed and high-severity effects (henceforth 'high severity wildfires') and asked: (1) How do post-fire woody fuel deposition and decay influence potential future wildfire severity with increasing time since wildfire? (2) Does post-fire logging reduce potential future wildfire severity over time? (3) Can prescribed fire alone reduce surface woody fuels sufficiently to mitigate the potential for subsequent high severity wildfires (reburns)? (4) Does post-fire logging facilitate prescribed fire use for managing fuels and potential wildfire severity after high severity wildfires? We used the First Order Fire Effects Model (FOFEM), along with empirical fuels data from a retrospective field study, to simulate time and treatment effects on fuel consumption, fire intensity, and fire effects under wildfire and prescribed fire conditions. We discuss the implications of our results for developing fuels management approaches following high severity wildfires.

Methods

Study area

For this study, we used field-based measurements of surface woody fuels obtained from a 39-year chronosequence of high-severity wildfires that burned in eastern Washington and Oregon, USA (Fig. 1) between 1970 and 2007 (Peterson *et al.* 2015, 2023*a*). We focused on dry conifer forests with similar low to mixed-severity and frequent (5–45 year mean fire return interval) historical fire regimes (Agee 1996; Everett *et al.* 2000; Wright and Agee 2004; Johnston *et al.* 2016). In these forest types, ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziessii*) are typically the dominant species. Co-occurring species include lodgepole pine (*Pinus contorta*), western larch (*Larix occidentalis*), western juniper (*Juniperus* occidentalis) and true firs (*Abies grandis*, *A. concolor*, *A. magnifica*). These forest types have experienced uncharacteristically large areas of high-severity wildfire in recent decades (Haugo *et al.* 2019), focusing attention on the need for forest restoration and fuel reduction treatments.

In this region, ponderosa pine and dry mixed conifer forests are found at low to middle elevations, ranging from 200 to 1000 m above sea level in eastern Washington and up to 1800 m in central Oregon. Climatic conditions vary with elevation, with mean annual precipitation ranging from about 35 cm at lower elevations dominated by ponderosa pine to over 100 cm in higher elevation mixed-conifer forests. Winters are typically cold and wet. Warm, dry summers

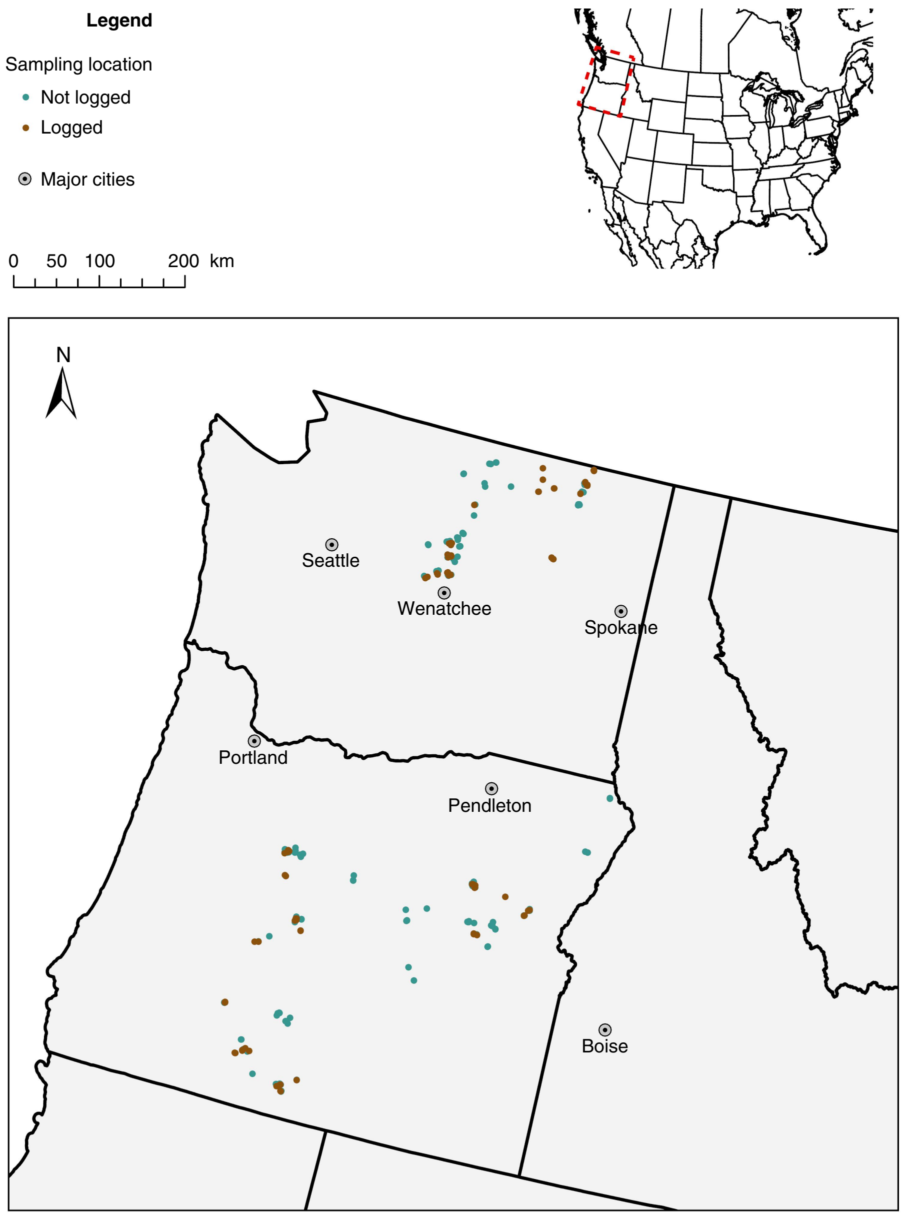

Fig. 1. Sampling locations in eastern Washington and Oregon, USA, shown by post-fire logging treatment.

produce weather and fuel moisture conditions favorable to wildfires.

Surface woody fuel measurements

To simulate the impact of post-fire management on subsequent fire effects, we used surface woody fuel measurements collected from high-severity patches within 68 wildfires that burned between 1970 and 2007 in dry conifer forests of eastern Washington and Oregon (Peterson *et al.* 2015, 2023*a*). Temporal patterns of fuel accumulation and snag decomposition based on these data have been published previously (Peterson *et al.* 2015, 2023*a*), but we briefly describe the data collection methods here because we used these surface woody fuel measurements to simulate the potential effects of prescribed fire and wildfire reburns on logged and unlogged stands. We measured fuels within 1–16 stands in each wildfire, resulting in a total of 255 sampled stands. Ninety-six of the stands had been logged following wildfire and 159 had not been logged. We selected logged stands based on evidence of significant post-fire logging, such as extensive stumps, but did not attempt to control for logging method. We did not have information on when post-fire logging took place relative to high severity fire, but standard practice during this time was to harvest within 1–2 years of wildfire to avoid loss of economic value from wood decay (Peterson *et al.* 2009). Therefore, our results can be considered representative of common post-fire logging practices used in the interior Pacific Northwest from 1970 through 2008 but cannot be tied to specific post-fire logging practices. We reconstructed pre-fire stand basal area from diameter measurements on standing dead trees, fallen dead trees, and cut stumps where we judged the trees to have been living at the time of the wildfire. Site selection and surface woody fuel sampling protocols are described in more detail by Peterson *et al.* (2015).

Within each stand, we surveyed surface woody fuels on three to seven 20-m fuel transects radiating from the plot center. We tallied surface woody fuels along the fuel transects by four diameter classes that correspond to the time lag fuel moisture classes used in fire effects modeling: 1-h fuels (0–0.6 cm diameter), 10-h fuels (0.7–2.5 cm diameter), 100-h fuels (2.6–7.6 cm diameter) and 1000-h fuels (>7.6 cm diameter). We measured the 1- and 10-h fuels along the first 2-m segment of each transect and 100-h fuels on the first 3-m segment of each transect. For 1000-h fuels, we recorded the fuel diameter and decay condition (sound or rotten) at the intersection with the transect tape over the entire 20 m. We calculated estimated fuel mass (Mg ha^{-1}) for each size class on individual transects (Brown 1974) and then averaged across all the transects within each stand to get stand-level fuel mass estimates.

Simulated fire effects

We conducted a simulation experiment using the BURNUP model as implemented in FOFEM (Albini and Reinhardt 1995, 1997; Albini *et al.* 1995; Lutes 2020) to evaluate how changes in fuelbeds with increasing time since fire and post-fire management (logged versus unlogged stands) influenced potential subsequent fire effects. We used the measured fuels data from (Peterson *et al.* 2015, 2023*a*) to simulate three future fire scenarios on stands that varied in post-fire management status (logged or unlogged) and time since initial high-severity fire. Our three future fire scenarios included (1) a summer wildfire burning under 97th percentile weather conditions, (2) a spring prescribed burn, and (3) a spring prescribed burn followed 10 years later by 97th percentile summer wildfire, described in more detail below.

BURNUP is a fuel consumption model that predicts heat transfer from smaller to larger fuels based on fuel loadings and has been calibrated and validated in previous work (Albini *et al.* 1995; Albini and Reinhardt 1997). Fuel inputs to the model include fuel size class, SAV, biomass and fuel moisture. The model simulates heat transfer and fuel consumption hierarchically based on size class, which is then used in FOFEM to calculate fireline intensity and fire effects such as fire duration, particulate emissions and soil heating (Lutes 2020). After an initial ignition, heat is transferred to the smallest size classes first (i.e. litter) and then transferred to progressively larger fuels such that consumption of larger fuels depends on interactions with the smaller size classes of fuels. By including interactions between fuels and including coarse woody debris, the BURNUP model may be better able to simulate reburn fire effects than fire behavior models, such as Rothermel (1972) that only use fine surface fuels (Kennedy *et al.* 2024).

To prepare our data for simulations, we first classified each study stand by post-fire treatment and time since fire. Post-fire treatments included logging shortly after wildfire or no logging. We grouped stands into six age classes based on the years since wildfire at the time of sampling: 1–5, 6–10, 11–15, 16–20, 21–25, or >25 years (Table 1). This classification system produced 12 groups with 7–48 stands per group (Table 1).

Then, we constructed fuelbeds for each sampled stand. BURNUP requires fuel biomass estimates for surface woody fuels, litter, live herbaceous fuels and live shrub fuels (Table 2). We used empirical fuel loads for 1-, 10-, 100- and 1000-h fuels measured for each stand (Peterson *et al.* 2015, 2023*a*), subdividing the 1000-h fuel loads into four diameter classes (7.6–15.2, 15.2–22.8, 22.8–51 and ≥51 cm) and two decay classes (sound and rotten). However, we did not have field measurements for duff, litter, live herbaceous or live shrub fuel loads. To help develop reasonable values for these fuel loads, we conducted a sensitivity analysis of modeled fire effects to different litter, live herbaceous and live shrub fuel loads over time since fire (Supplementary Material). Live herbaceous and live shrub fuel loads had little impact on simulated fire effects, but litter loads influenced simulated fire effects over time, particularly for particulate matter ($PM_{2.5}$) emissions (Supplementary Material). Therefore, we selected default values for live herbaceous and live shrub fuel loads from the SH1 Low load dry climate shrub fuel model from Scott and Burgan (2005), as representative of severely burned stands where the primary carrier of fire would be recovering woody shrub vegetation along with some grasses and forbs. Since the model was sensitive to litter loads, we allowed litter to vary based on time since

Table 1. Number of sampled stands by post-fire management and years since wildfire.

Post-fire management	Time since fire (years)	Number of plots
Not logged	1–5	27
Not logged	6–10	39
Not logged	11–15	40
Not logged	16–20	35
Not logged	21–25	9
Not logged	>25	9
Logged	1–5	7
Logged	6–10	24
Logged	11–15	22
Logged	16–20	15
Logged	21–25	19
Logged	>25	9

Table 2. Simulation design and First Order Fire Effects Model (FOFEM) parameters for examining the effects of post-fire management on future fire effects.

Fire scenario				**Wildfire**	**Prescribed fire**
Fire weather parameters		**Windspeed ($m\ s^{-1}$)**		**4.05**	**1.03**
		Ambient temperature (°C)		**34.4**	**14**
	Fuel class	**Fuel load ($Mg\ ha^{-1}$)**	**SAV (m^{-1})**	**Fuel moisture[A] (%)**	
Fuel parameters[B]	Litter	Estimated based on Dunn and Bailey (2015)	8200	1	9
	Live herbaceous	0.34	NA	NA	NA
	Live shrub	2.91	NA	NA	NA
	1-h	Field measured	6562	1	9
	10-h	Field measured	357.6	3	11
	100-h	Field measured	98.4	5	13
	7.6–15.2 cm	Field measured	39.4	7 (17.5)	20 (50)
	15.2–22.8 cm	Field measured	21.9	7 (17.5)	20 (50)
	22.8–51 cm	Field measured	12.7	7 (17.5)	20 (50)
	>51 cm	Field measured	5.9	7 (17.5)	20 (50)

[A]Fuel moisture levels for 10- and 1000-h sound fuels were based on published 97th percentile fire weather values from northcentral Washington (wildfire scenario; Radcliffe *et al.* 2024) and published values from spring prescribed fire treatments implemented in the Mission Creek Fire and Fire Surrogates Study in northcentral Washington (Agee and Lolley 2006). FOFEM sets the 1- and 100-h fuels to 2% lower and higher, respectively, than the 10-h fuel moisture values (Lutes 2020). FOFEM sets 1000-h rotten fuel moisture to 250% of sound fuel moisture; for each 1000-h fuel class, sound fuel moisture is shown with the rotten fuel moisture in parentheses.

[B]Fuel loads for the 1-, 10-, 100- and 1000-h fuels were based on the stand-level estimates from Peterson *et al.* (2015, 2023*a*), values are not shown in the table because these loadings varied between stands and between logging treatments. Since FOFEM also requires fuel loads for duff, litter and herbaceous fuels, we used default values associated with the SH1 Low load dry climate shrub fuel model from Scott and Burgan (2005), which we selected as representative of stands recovering from high-severity wildfire. We applied the litter accumulation equation from Dunn and Bailey (2015) to estimate litter loads based on time since fire. Duff fuel loads were set to zero so that FOFEM would implement the non-duff model and simulate fire effects based on surface woody fuel loads.

high-severity wildfire. We applied litter accumulation equations following high-severity wildfires in eastern Oregon to estimate litter loads for each of our stands based on time since fire for each individual stand, where litter increased linearly at a rate of 0.90 $Mg\ ha^{-1}\ year^{-1}$ (Dunn and Bailey 2015). We conducted all the simulations using the no-duff soil heating model in BURNUP, as that simulates soil heating based on heat produced from combustion of the woody, litter, herbaceous and shrub fuels rather than from combustion of the duff layer (Lutes 2020). We chose this option because we were primarily interested in how changes in surface woody fuels would affect soil heating. We used the default SAV values for litter and for each of the 1000-h diameter classes (Table 2; Lutes 2020). For the 1-, 10- and 100-h fuel classes, we used SAV values typical of timber litter fuel models (Table 2; Scott and Burgan 2005).

Finally, we simulated burning at each stand under three fire scenarios representing common summer wildfire conditions, spring prescribed burning conditions and spring prescribed fire followed by a summer wildfire (Table 2). For the summer wildfire simulations, we used fuel moisture, ambient air temperature and windspeed parameters from the 'severe' wildfire scenario presented by Radcliffe *et al.* (2024), which was based on 97th percentile values for fire season conditions from Remote Automated Weather Stations (RAWS) within the study region. For the prescribed fire scenario, we used fuel moisture values from a spring prescribed fire study in northcentral Washington (Agee and Lolley 2006) along with windspeeds from the 'mild' wildfire scenario of Radcliffe *et al.* (2024) and air temperatures from local prescribed fire activities (J. Barnes 2006, unpubl. data; P. Ohlsen 2007, unpubl. data). FOFEM sets the fuel moisture of 1- and 100-h fuels to 2% lower and higher, respectively, than the 10-h fuel moisture (Lutes 2020), so we parameterized the 10- and 1000-h fuel moisture values and allowed the model to set 1- and 100-h fuel moisture values.

In order to assess whether prescribed fire, with or without logging, has the potential to mitigate subsequent wildfire effects, we simulated a wildfire reburn 10 years following our simulated prescribed fire. We used the output from the simulated prescribed fire to simulate a summer wildfire with the same 97th percentile fuel moisture and weather conditions as our simulated summer wildfire described above. We assumed that shrub and herbaceous regrowth would recover during the 10 years between simulated prescribed fire and the simulated wildfire but primarily contribute to small diameter fuels (1- and 10-h) and litter, so we adjusted these fuel loads to account for this regrowth. Our prescribed fire simulation consumed all litter, live herbaceous and live shrub fuels across all our stands, so we reset the live herbaceous and live shrub fuel loads to those of the SH1 fuel model from Scott and Burgan (2005). Since we assumed a 10-year interval between simulated prescribed and wildfire, we applied the litter accumulation rate of 0.9 Mg ha^{-1} $year^{-1}$ over 10 years from Dunn and Bailey (2015) to calculate litter loads. Assuming that most regrowth would be from shrubs, herbs and small seedlings or saplings, we did not add any fuel accumulation for 100- or 1000-h fuels between the simulated prescribed fire and the wildfire simulation. Rather, we used the 100- and 1000-h fuel loads that the model predicted remained in each stand after the simulated prescribed fire. We did have to account for differences between BURNUP input and output loads for 1000-h fuels, however. In the input files, BURNUP allows division of 1000-h fuels into diameter classes, as described above, but only provides output fuel loads for total 1000-h sound and total 1000-h rotten fuels. Based on an analysis of published data before and after a prescribed fire treatment in northcentral Washington (Peterson *et al.* 2025), we found that, although 1000-h fuels are consumed by prescribed fire, the proportional size distribution of sound and rotten fuel loads in these 7.6 cm diameter classes remains relatively consistent before and after prescribed fire. Therefore, we calculated the proportional size distribution of 1000-h sound and rotten fuel loads in the four diameter classes for each stand in the field measured data (which were inputs to the simulated prescribed fire) and applied that proportional distribution to the 1000-h fuels loads remaining following the simulated prescribed fire.

Analysis

We used analysis of covariance (ANCOVA) to assess the effects of post-fire logging and time since fire on woody fuel loads and simulated fire effects, including fuel consumption, maximum fire reaction intensity (hereafter, fire intensity), fire duration, and particulate emissions under summer wildfire and spring prescribed fire conditions. The ANCOVA models included the post-fire treatment (logged or not logged), a time since fire classification variable (5-year intervals) and a two-way interaction term as predictor variables. We also included pre-fire stand basal area (m^2 ha^{-1}) as a continuous covariate in each model, as prior studies and preliminary data analyses showed that higher pre-fire stand basal area was associated with higher potential fuel deposition (Peterson *et al.* 2015), higher simulated fuel consumption, and that simulated fuel consumption was highly correlated with simulated fire effects. We centered the pre-fire basal area predictor around the mean from all 255 stands (32.7 Mg ha^{-1}) and fit final ANCOVA models without a general intercept term so that model estimates of post-fire treatment and time since fire effects (model parameters) would represent expected outcomes for a stand with the mean pre-fire basal area. We tested the main effect of pre-fire basal area, as well as its interaction with time since fire. To satisfy assumptions of normality in model residuals, we square root-transformed each of the response variables prior to analysis. We used a significance threshold of 1% ($P < 0.01$) for Type I errors when testing the significance of model main effects, interaction effects and pairwise differences among post-fire treatments within each time period. We performed the ANCOVA analysis using the SAS GLIMMIX procedure (SAS/STAT software, version 15.3, SAS Institute) and used the SLICE option for the pairwise comparison tests. Finally, we qualitatively compared the proportion of stands reaching a soil heating threshold considered lethal to plant material (60°C) at various soil depths between logging treatments and fire scenarios.

Results

Mean surface woody fuels varied significantly with increasing time since wildfire, between logged and unlogged sites sampled at similar times since wildfire, and with pre-fire stand basal area. Although this has been reported previously by Peterson *et al.* (2015, 2023*a*) for this dataset, we present the results here in similar format to our simulated consumption from our simulated fires (Fig. 2) to clarify the links between observed fuel loads and simulated fuel consumption and simulated fire effects. Pre-fire stand basal area was a highly significant covariate ($P < 0.005$) for all our statistical models, showing that woody fuel accumulation, simulated woody fuel consumption, fire behavior and fire effects, were all positively correlated with pre-fire stand basal area (or, more generally, stand basal area killed by wildfire).

Temporal patterns of fuel accumulation and consumption

Mean surface woody fuels varied with time since wildfire. On unlogged sites, fine woody fuel loads (1-, 10- and 100-h fuels) were lowest on sites sampled in the first 5 years after high severity wildfire (mean = 5.8 Mg ha^{-1}; Table 3), increased to a maximum on sites sampled 11–15 years after fire (mean = 11.2 Mg ha^{-1}), and then declined with increasing time since fire (Table 3). Similarly, sound 1000-h woody fuels were low on stands sampled in the first 5 year after fire (mean = 34.8 Mg ha^{-1}), reached maximum levels 11–15 years after fire (mean = 71.5 Mg ha^{-1}), and then declined sharply with increasing time since fire, reaching a mean of 27.1 Mg ha^{-1} when time since fire exceeded 25 years (Table 3). Rotten 1000-h woody fuels were low on sites sampled during the first 15 years after fire, with mean fuel loads below 10 Mg ha^{-1}, and then increased steadily with increasing time since fire, reaching a peak of 48.7 Mg ha^{-1} in unlogged stands sampled more than 25 years after wildfire (Table 3).

Measured fuel loads varied significantly with pre-fire basal area. Higher pre-fire basal area was positively correlated with fine fuel, 1000-h sound and 1000-h rotten fuels, although the association was weaker for rotten fuels than

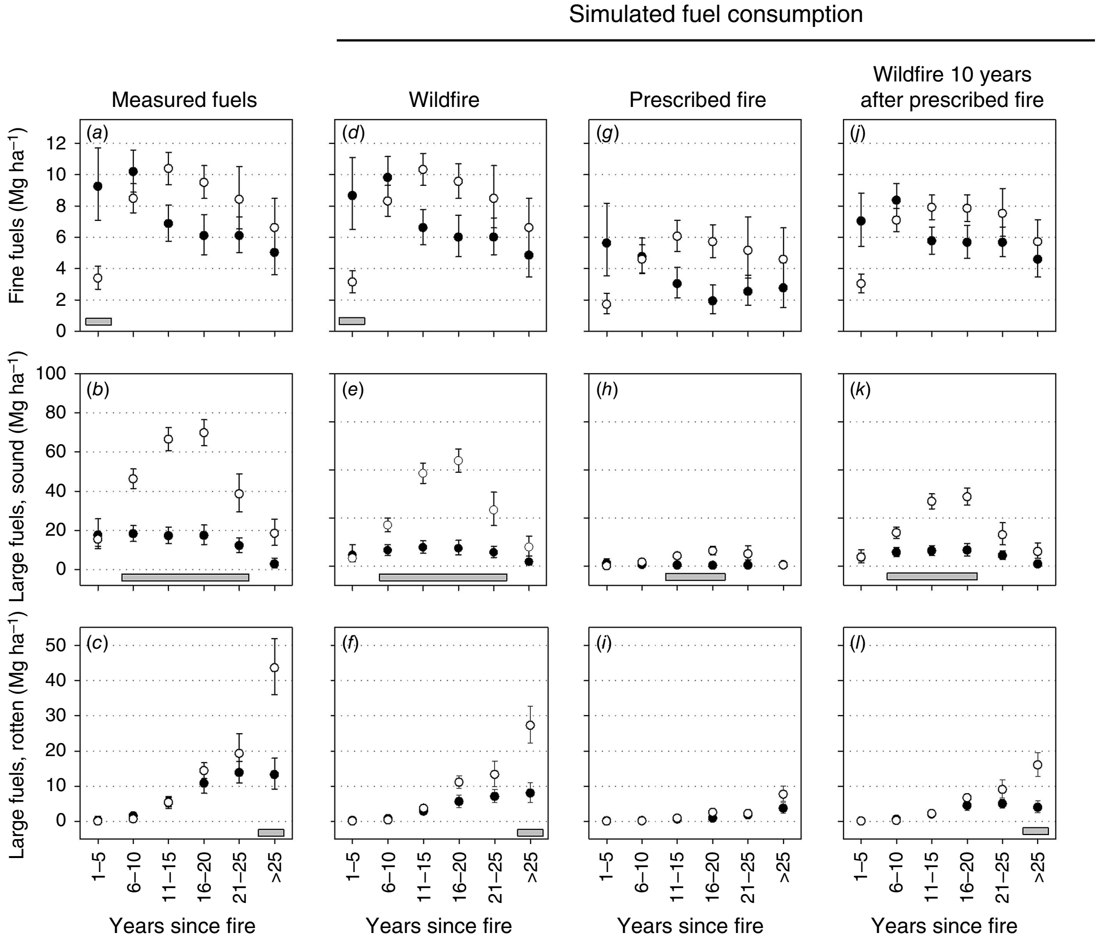

Fig. 2. Temporal patterns in (*a–c*) measured fuel loads after high-severity wildfire (data from Peterson *et al.* 2023*b*), (*d–f*) fuel consumption from simulated wildfire, (*g–i*) simulated prescribed fire, and (*j–l*) simulated wildfire 10 years after prescribed fire for stands with and without post-fire logging. Open circles represent unlogged stands and solid circles represent logged stands. Shaded bars indicate significant differences in the least-squared means from our analysis of covariance (ANCOVA) analysis at α = 0.01.

the other fuel classes (Fig. 3). Interactions between pre-fire basal area and time since fire were not significant in any of our ANCOVA models. Here, we present mean measured and simulated fuel loads (raw values; Table 3) and statistical differences after accounting for basal area (Figs 2, 4).

Post-fire logging altered temporal patterns of woody fuel accumulation across size classes. On logged sites, mean fine woody fuels were highest on sites sampled within the first 5–10 years after wildfire and then declined with increasing time since fire (Table 3). Mean fine woody fuels were higher in logged stands (9.4 Mg ha^{-1}) than in unlogged stands (5.8 Mg ha^{-1}) sampled within the first 5 years after wildfire and these differences were statistically significant after accounting for pre-fire stand basal area (Fig. 2*a*). Mean fine fuel loads were slightly lower on logged than unlogged stands sampled more than 16 years post-wildfire (Table 3). However, after accounting for pre-fire basal area, differences between logged and unlogged stands were not statistically significant (Fig. 2*a*) for stands sampled more than 5 years after wildfire. Mean sound 1000-h fuels were lower in logged stands than in unlogged stands sampled 6–25 years after wildfire, staying below 28 Mg ha^{-1} in logged stands as sound 1000-h fuels increased sharply in unlogged stands to a peak of 71.5 Mg ha^{-1} 11–15 years after wildfire (Table 3). These differences in sound 1000-h fuel loads between logged and unlogged stands 6–25 years after wildfire remained significantly different after accounting for pre-fire basal area (Fig. 2*b*). Mean rotten 1000-h fuels were similar in logged and unlogged stands sampled within 25 years after fire (Table 3). But mean rotten 1000-h fuel loads were much higher in unlogged stands than logged stands >25 years after fire (48.7 and 15.9 Mg ha^{-1}, respectively; Table 3) and these differences remained significant in our models accounting for differences in stand basal area (Fig. 2*c*).

Projected woody fuel consumption across fire scenarios was proportional to existing fuel loads but varied with

Table 3. Measured and simulated consumption of fuel loads for fine fuels, 1000-h sound and 1000-h rotten fuels.

		Number of stands		Measured fuels (Mg ha^{-1})		Simulated fuel consumption (Mg ha^{-1}) Wildfire		Prescribed fire		Wildfire 10 years after prescribed fire	
Fuel class	Years since fire	Not logged	Logged	Not logged	Logged	Not logged	Logged	Not logged	Logged	Not logged	Logged
Fine fuels	1–5	7	27	5.8 (1.3)	9.4 (2.4)	5.6 (1.3)	8.9 (2.5)	4.1 (1.3)	6.5 (2.4)	4.7 (1.0)	6.7 (1.5)
	6–10	24	39	10.5 (1.5)	12.1 (1.5)	10.4 (1.5)	11.8 (1.6)	7.3 (1.6)	7.5 (1.8)	8.6 (1.3)	9.9 (1.3)
	11–15	22	40	11.2 (1.2)	6.5 (0.9)	11.2 (1.2)	6.3 (0.9)	8.0 (1.4)	3.3 (0.9)	8.6 (1.0)	5.3 (0.5)
	16–20	15	35	9.7 (1.1)	7.0 (0.9)	9.7 (1.1)	6.9 (0.9)	6.5 (1.2)	2.9 (0.9)	7.9 (0.8)	6.4 (0.8)
	21–25	19	9	8.7 (2.0)	7.3 (0.9)	8.7 (2.0)	7.3 (1.0)	6.2 (2.4)	4.2 (1.1)	7.6 (1.6)	6.6 (0.8)
	>25	9	9	6.9 (1.5)	5.1 (1.2)	6.9 (1.5)	5.0 (1.3)	5.3 (1.8)	3.6 (1.5)	5.9 (1.3)	4.6 (1.0)
Large fuels, sound	1–5	7	27	34.8 (8.7)	15.2 (4.5)	13.9 (5.5)	3.1 (1.2)	1.0 (0.6)	1.0 (0.7)	13.2 (5.5)	2.7 (0.9)
	6–10	24	39	55.0 (5.6)	27.2 (5.1)	24.9 (4.3)	12.0 (2.6)	6.6 (2.6)	2.9 (1.1)	18.8 (3.0)	9.6 (2.2)
	11–15	22	40	71.5 (7.1)	14.9 (2.0)	45.6 (6.5)	6.4 (1.3)	13.4 (5.1)	0.3 (0.3)	31.6 (4.5)	5.9 (1.2)
	16–20	15	35	69.3 (7.8)	22.6 (3.6)	45.9 (6.5)	10.4 (1.8)	13.6 (4.5)	1.6 (1.0)	31.2 (5.0)	8.7 (1.4)
	21–25	19	9	41.1 (12.6)	16.9 (2.9)	27.5 (10.8)	9.3 (2.2)	13.3 (8.7)	2.6 (1.5)	13.6 (3.6)	6.5 (1.4)
	>25	9	9	27.1 (15.0)	3.2 (1.6)	12.9 (9.5)	1.8 (0.9)	0.5 (0.3)	0.8 (0.5)	12.0 (9.4)	0.8 (0.4)
Large fuels, rotten	1–5	7	27	0.5 (0.3)	0.4 (0.3)	0.2 (0.1)	0.4 (0.3)	0.1 (0.1)	0.2 (0.2)	0.2 (0.1)	0.1 (0.1)
	6–10	24	39	2.9 (1.0)	3.4 (0.9)	1.7 (0.6)	3.4 (0.9)	0.7 (0.3)	1.8 (0.5)	1.0 (0.4)	1.2 (0.3)
	11–15	22	40	9.8 (2.1)	5.6 (1.2)	6.8 (1.5)	5.6 (1.2)	2.5 (0.9)	2.8 (0.6)	4.3 (1.1)	2.4 (0.6)
	16–20	15	35	19.1 (3.5)	14.5 (4.0)	15.0 (3.1)	14.5 (4.0)	5.9 (2.7)	7.4 (1.7)	9.1 (1.6)	5.9 (1.7)
	21–25	19	9	26.4 (14.8)	17.4 (3.1)	19.6 (12.2)	17.4 (3.1)	2.9 (1.1)	9.5 (1.8)	16.9 (12.4)	6.4 (1.2)
	>25	9	9	48.7 (12.5)	15.9 (4.8)	31.9 (9.8)	15.9 (4.8)	13.5 (6.8)	10.1 (3.6)	17.9 (3.7)	4.9 (1.4)

Values shown are means (standard error) across logged and unlogged stands for each time period and scenario.

simulated fire scenario, presence of post-fire logging and fuel size class. Under simulated wildfire conditions, BURNUP simulated mean woody fuel consumption (across logging status and all time classes) of 98% of the measured fine woody fuels, 50% of the 1000-h sound woody fuels and 61% of the 1000-h rotten woody fuels (Fig. 4*a–c*).

Simulated wildfire consumed significantly more fine fuels in logged than unlogged stands in the first 5 years after wildfire, due to higher fuel availability in these stands (Fig. 2*d*). Simulated fine fuel consumption between logged and unlogged stands was not significantly different for other time periods (Fig. 2*d*). Following patterns in measured fuel availability, simulated wildfire consumed significantly more sound 1000-h fuels in unlogged than logged stands sampled 6–25 years after the initial wildfire (Fig. 2*e*). Similarly, rotten fuel loads and simulated wildfire consumption of rotten fuels did not differ significantly for the first 25 years after wildfire (Fig. 2*f*). Only in the stands sampled more than 25 years after the initial wildfire did rotten fuel loads and simulated consumption by wildfire differ significantly (Fig. 2*f*).

Projected woody fuel consumption was much lower under the simulated prescribed fire. The model simulated mean percent consumption of 65% of the fine woody fuels, 13% of the 1000-h sound woody fuels, and 23% of the 1000-h rotten woody fuels across logging status and all time classes (Fig. 4*d–f*). In many stands, simulated prescribed fire consumed little to none of the available fuels, particularly for 1000-h fuels, although it was somewhat more effective at reducing fine fuels. Following temporal patterns in fuel availability, post-fire logging increased fine woody fuel consumption by simulated prescribed fire on sites sampled within 5 years of the initial wildfire (Fig. 2*a, g*), although this difference was not statistically significant. Post-fire logging reduced availability and simulated consumption of 1000-h sound and rotten woody fuels as time since fire increased, but the simulated consumption of 1000-h fuels by prescribed fire was quite low compared to available fuel loads

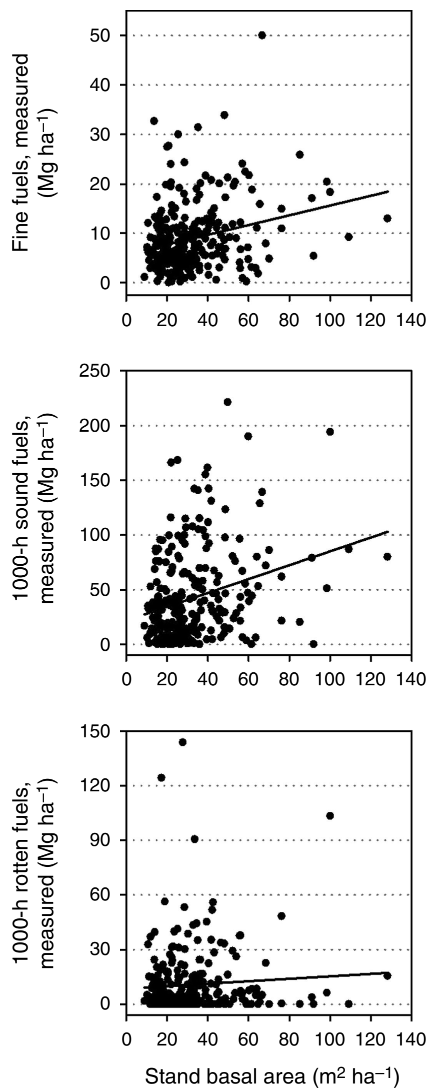

Fig. 3. Relationship between pre-fire stand basal area and measured fine woody fuel loads (1-, 10- and 100-h fuels), sound 1000-h fuel loads and rotten 1000-h fuels loads. Pre-fire basal area refers to the basal area of logged and unlogged stands prior to the initial high-severity wildfire, estimated from the diameter of fire-killed trees (standing or fallen) and from stumps in logged stands (see Peterson *et al.* 2015).

(Fig. 2*b, c, h, i*). Low percent fuel consumption under simulated prescribed fire conditions was generally associated with low fuel loads in smaller diameter classes. Because simulated fuel consumption in BURNUP depends on heat transfer from smaller to larger fuels, plots with low percent consumption of 100-h fuels tended to have low total loadings in the 1- and 10-h fuel classes and plots with low percent consumption of 1000-h fuels tended to have low fine woody fuel loadings.

In our simulated wildfire reburning after prescribed fire scenario, simulated fuel consumption patterns were intermediate compared to wildfire alone or prescribed fire alone. In this scenario, the model simulated an average consumption of 97% of the fine woody fuels, 42% of the 1000-h sound woody fuels, and 52% of the 1000-h rotten fuels across logging status and time classes (Fig. 4*g–i*). We assumed fine fuels would recover in the intervening 10 years between fires and simulated consumption of fine fuels is slightly lower than in wildfire alone but higher than for prescribed fire alone (Fig. 2*d, g, j*). The simulated wildfire reburn consumed more of the 1000-h sound and rotten fuels than simulated prescribed fire (Fig. 2*h, i, k, l*), but simulated consumption of these fuels was lower than for the wildfire-only scenario (Fig. 2*e, f, k, l*). As with the wildfire-only simulations, simulated consumption of 1000-h fuels by wildfire after prescribed fire reflected patterns in measured fuel availability. In this scenario, post-fire logging significantly reduced simulated sound 1000-h fuel consumption in stands sampled 6–20 years after the initial wildfire, when sound fuel loads were highest (Fig. 2*b, k*). Similarly, only in stands sampled more than 25 years after fire were measured rotten 1000-h fuels significantly higher in unlogged than logged stands and that is when our simulations suggest that post-fire logging would significantly reduce rotten 1000-h fuel consumption by wildfire following prescribed fire (Fig. 2*c, l*).

Post-fire logging impacts on fire effects

Projected maximum fire intensity varied through time and between logged and unlogged stands under simulated fire scenarios. The simulated wildfire scenario led to the highest projected fire intensities, followed by the simulated wildfire after prescribed fire and predicted fire intensities were lowest when we simulated prescribed fire on its own (Fig. 5*a, d, g*). In our simulated wildfire, mean maximum fire intensity in unlogged stands was lowest for stands sampled 1–5 years after fire, peaked on sites sampled between 11 and 20 years after fire and then declined beyond 20 years (Fig. 5*a*). Post-fire logging increased simulated wildfire intensities compared to unlogged stands for stands sampled within 10 years after the initial fire, but this difference was not significant. However, on sites sampled 11–20 years after the initial wildfire post-fire logging significantly reduced maximum simulated wildfire intensity. Simulated fire intensities were much lower for prescribed fire than for wildfire and post-fire logging had no significant impact on simulated prescribed fire intensities (Fig. 5*d*). When we simulated a prescribed fire followed by a wildfire, the temporal patterns in predicted fire intensities for logged and unlogged stands were similar to the simulated wildfire scenario, but simulated intensities were much lower than in wildfire alone (Fig. 5*a, g*). As in the wildfire scenario, post-fire logging significantly reduced simulated fire intensities in the wildfire following prescribed fire scenario for stands sampled 11–20 years after the initial wildfire (Fig. 5*g*).

Burn severity metrics – for particulate emissions, fire duration and soil heating – were highly correlated with total fuel consumption (r = 0.66–0.99, P < 0.0001) across all our simulated fire scenarios, so temporal patterns of burn severity metrics closely resembled the temporal patterns of

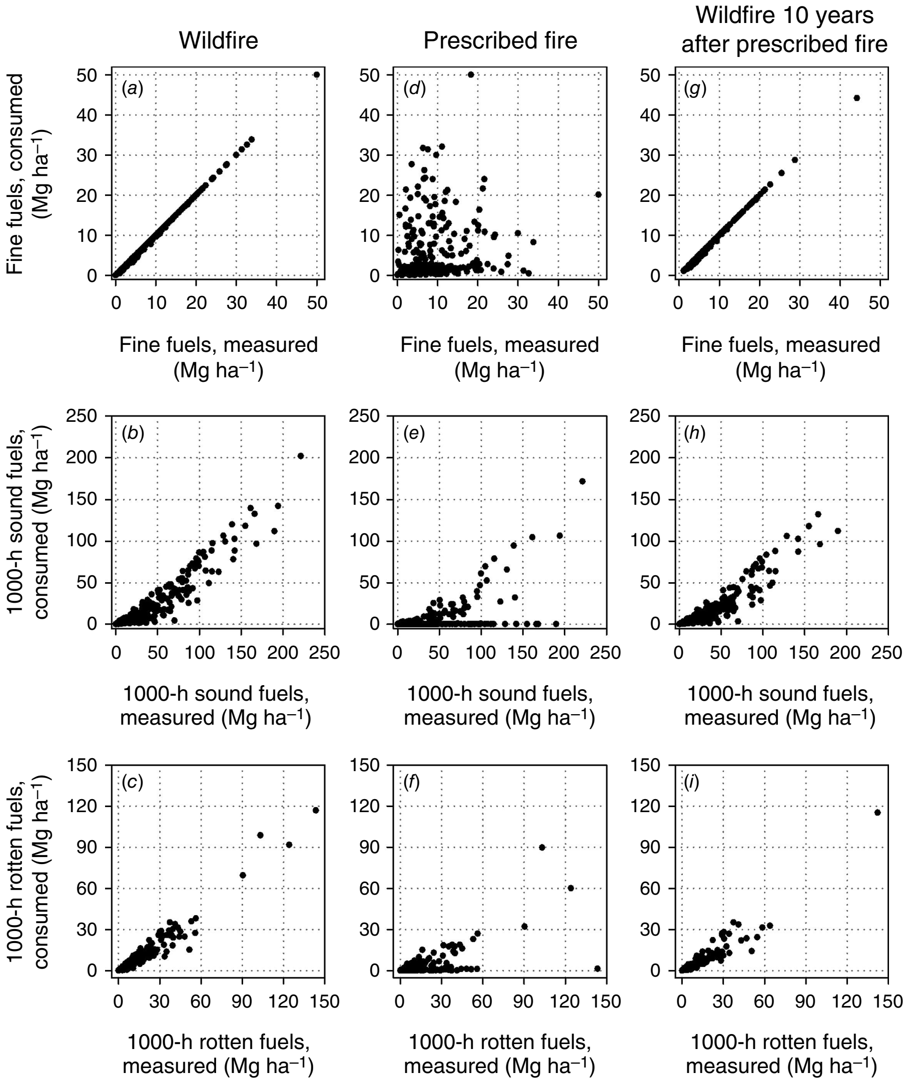

Fig. 4. Relationship between measured fuel loads and predicted fuel consumption for (*a–c*) simulated wildfire, (*d–f*) simulated prescribed fire and (*g–i*) simulated wildfire following prescribed fire for fine woody fuels (1-, 10- and 100-h fuels), sound 1000-h fuels and rotten 1000-h fuels.

total surface fuel loadings and fuel consumption (Figs 2, 4). Predicted particulate emissions ($PM_{2.5}$) were highest in the simulated wildfire and considerably lower under simulated prescribed fire (Fig. 5*b*, *e*). Simulated wildfire following a prescribed fire led to lower predicted emissions than in the simulated wildfire but higher than for a simulated prescribed fire on its own (Fig. 5*b*, *e*, *h*). Post-fire logging significantly reduced mean particulate emissions under simulated wildfire alone and under simulated wildfire following prescribed fire for stands sampled >11 years after the initial fire (Fig. 5*b*, *h*). Under simulated prescribed fire alone, post-fire logging significantly reduced emissions for stands sampled 11–20 years after the initial wildfire (Fig. 2*e*). Under simulated wildfire, fire duration in unlogged stands was lowest for stands sampled 1–5 years after fire and peaked for stands sampled 16–20 years after the initial wildfire (Fig. 5*c*).

Post-fire logging significantly reduced simulated wildfire duration in stands sampled 6–20 years and more than 25 years after the initial wildfire (Fig. 5*c*). Simulations of wildfire following prescribed fire showed similar patterns of predicted fire duration to the simulation of wildfire alone (Fig. 5*i*). Under simulated prescribed fire alone, predicted fire durations were initially low and steadily increased with time since initial wildfire (Fig. 5*f*). Post-fire logging did not significantly impact simulated prescribed fire duration at any time period (Fig. 5*f*).

Simulated wildfire generated the most soil heating of all the fire scenarios, but post-fire logging also reduced simulated depths of soil heating in all fire scenarios (Fig. 6). Soil temperatures were projected to reach 60°C at depths of 3 cm or more for 18% (29 of 159) of unlogged stands under simulated wildfire conditions, 1% (2 of 159) of unlogged stands under simulated prescribed fire and 10% (16 of 159) of unlogged stands under simulated wildfire following prescribed fire (Fig. 6). In unlogged stands, soil heating was highest in stands sampled 16–20 years after the initial fire for all simulated fire scenarios but was highest for the

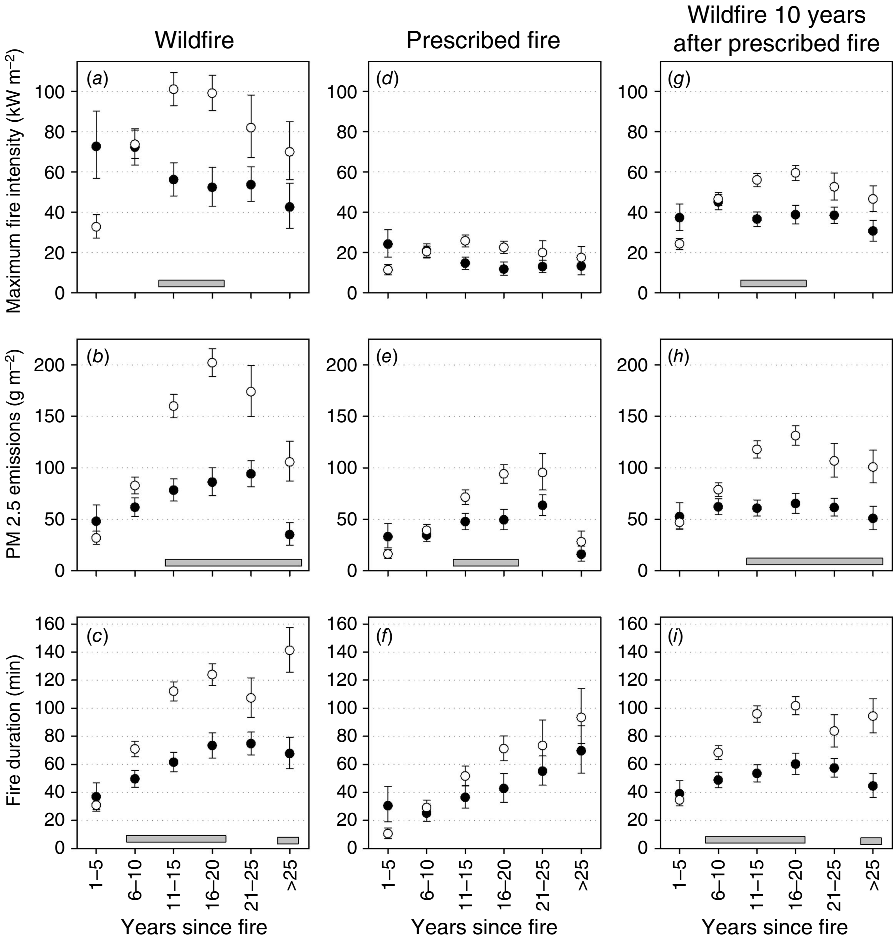

Fig. 5. Temporal patterns in fire behavior and effects between logged and unlogged stands for (*a–c*) simulated wildfires, (*d–f*) simulated prescribed fires and (*g–i*) simulated wildfire 10 years after prescribed fire. Open circles represent unlogged stands and solid circles represent logged stands. Shaded bars indicate significant differences in the least-squared means from our analysis of covariance (ANCOVA) analysis at $\alpha = 0.01$.

simulated wildfire. Simulated prescribed fires predominantly only heated soils to 60°C at the soil surface. None of the logged stands under any of the simulated fire scenarios reached 60°C at depths of 3 cm or more (Fig. 6).

Discussion

The severity of repeat wildfires tends to reflect that of the prior wildfire: high severity wildfires are generally followed by high severity reburns, low severity wildfires (or prescribed fires) tend to reburn at low severity (Coppoletta *et al.* 2016; Prichard *et al.* 2017). After high severity wildfires, post-fire fuels management is often proposed to mitigate future threats to human health, human property and natural resources during reburns, particularly in forests with short mean fire return intervals (Prichard *et al.* 2021; Stevens *et al.* 2021; Larson *et al.* 2022). This study shows that woody fuel dynamics following high severity wildfires strongly influenced simulated subsequent wildfire (reburn) behavior and impacts. Our simulations also suggest that post-fire logging and prescribed burning can reduce potential reburn intensity and severity and associated threats to human health and property by limiting fuel accumulations over time, but the two treatments are more complementary than interchangeable. Post-fire logging effectively reduced large diameter woody fuel loads over time and associated fire effects but generated an initial pulse of fine fuels and elevated simulated wildfire intensity and severity immediately after harvest. In contrast, simulated prescribed fire alone reduced fine woody fuels but had little impact on large diameter fuels. Post-fire logging in combination with simulated prescribed fire reduced the severity of a simulated reburn, indicating that a combination of post-fire management approaches could help mitigate potential future fire effects. Our results suggest that neither post-fire logging nor prescribed fire can independently address all aspects of post-fire fuels management but will likely need to be tailored to specific post-fire conditions and management objectives.

Post-fire fuel dynamics and reburn severity

We found that changes in surface woody fuel loads with increasing time since wildfire produced significant changes in potential reburn intensity and severity under simulated summer wildfire conditions on unlogged stands. Low surface woody fuel loads limited simulated fuel consumption and associated fire effects for wildfires occurring within 10 years

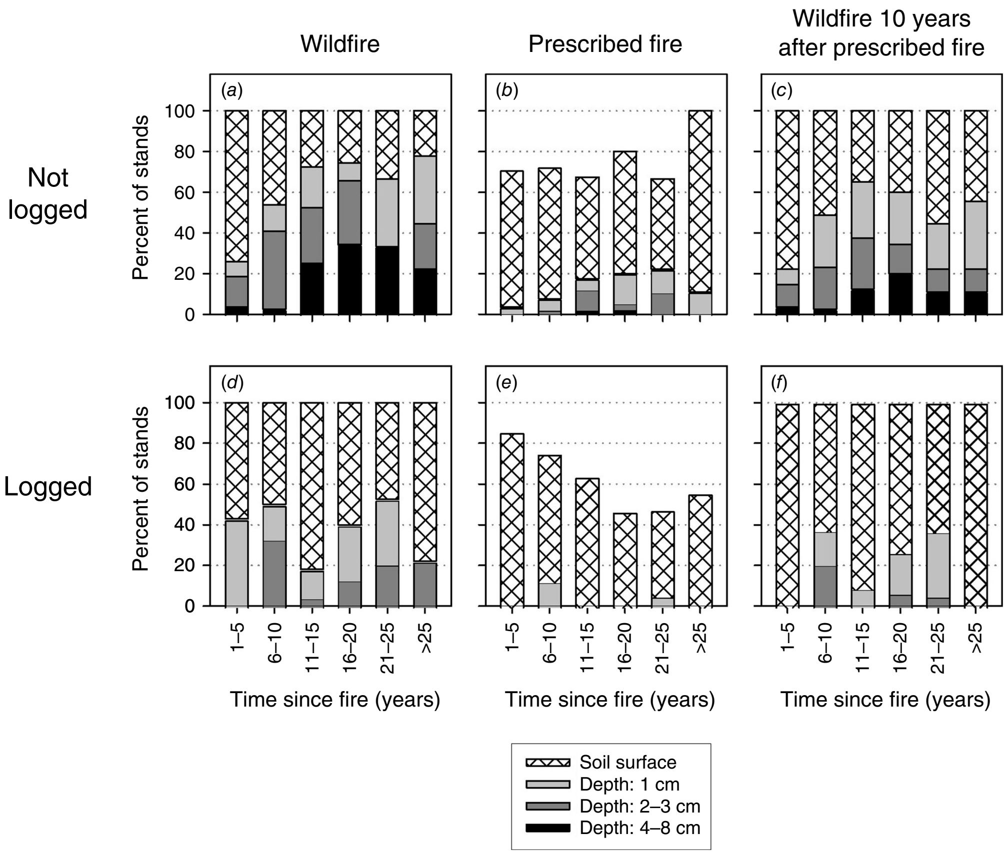

Fig. 6. Percent of stands reaching temperatures lethal to plant material (60°C) at different soil depths for simulated wildfire, prescribed fire and wildfire following prescribed fire in (*a*–*c*) unlogged and (*d*–*f*) logged stands.

of the initial wildfire. Surface woody fuel loads increased with increasing time since fire and reached maximum mean levels 11–20 years after wildfire, a period that also featured the greatest fuel consumption, maximum fire intensity, particulate emissions, fire duration and soil heating during simulated wildfires. These results support the idea that fuels generated from pulses of fire-killed trees can influence the intensity and severity of subsequent wildfires (Collins *et al.* 2009; Parks *et al.* 2015; Coppoletta *et al.* 2016; Harvey *et al.* 2016).

The intensity and severity of these fuel-driven 'reburns' is driven by the density of fire-killed trees, the interval between fires and fire weather during the second fire. The density of fire-killed trees regulates the volume of new surface woody fuels that will be deposited over time because of snag decomposition processes (Ritchie and Knapp 2014; Peterson *et al.* 2023*a*). Time since fire affects surface woody fuels loads through snag decomposition, wood decay and associated changes in surface area to volume ratios, litter and duff accumulations, and understory vegetation structure and composition (Dunn and Bailey 2015; Peterson *et al.* 2015; Coppoletta *et al.* 2016; Lydersen *et al.* 2019), all of which can influence wildfire behavior and effects. Fire weather also influences wildfire behavior and effects through its effects on fuel moisture and temperature and the amount of heat needed to ignite fuels and sustain combustion processes; indeed, extreme fire weather (hot, dry and windy) is a common factor associated with large wildfires and high burn severity (Werth *et al.* 2016; Potter and McEvoy 2021). Our study shows that post-fire snag and fuel dynamics produce fuel conditions that could produce high severity reburns starting 5–10 years after stand-replacing wildfire and persisting for 30 years or more, given an ignition source and 97th percentile fire weather.

High severity reburns present significant threats to natural resources, human health and property, particularly when high severity burn patches are large. Long wildfire residence times and associated soil heating can greatly reduce soil carbon; alter soil structure, nutrient cycles and hydrological processes; and increase post-fire hazards from runoff and soil erosion (Neary *et al.* 1999; Certini 2005). Long wildfire residence times can also kill residual mature trees, regenerating forest trees and understory plants, thereby slowing post-fire forest recovery (Brown and Smith 2000). Heavy fuel loads make wildfires difficult to control and can threaten homes in nearby communities directly or through ember production. Large amounts and long duration of particulate matter emissions produce threats to human health, as these emissions are associated with increased risk of respiratory issues, cardiovascular disease, all-cause mortality and can exacerbate chronic health conditions (Jaffe *et al.* 2020; Rizzo and Rizzo 2025). Heavy loadings of large diameter fuels can also promote smoldering combustion for extended periods of time, which can then lead to increased soil heating (Brown 2003; Monsanto and Agee 2008; Ottmar 2014). Under our wildfire scenario, the model simulated temperatures at or above 60°C at soil depths up to 8 cm and the proportion of stands exposed to these temperatures increased with increasing 1000-h fuel loads. Exposure to temperatures above 60°C for 1 min or longer has been associated with meristematic tissue death (Hare 1961), so these findings indicate the potential for wildfire reburns to kill plants and inhibit tree regeneration and understory recovery when large diameter fuel loads are high.

Managing post-fire fuel dynamics and reburn severity with post-fire logging

Post-fire logging alters the pulse of post-fire woody fuel deposition and accumulation by removing a portion of the large woody debris and accelerating the deposition of fine and smaller coarse woody debris as logging slash. Consistent with prior studies, we found that post-fire logging initially increased surface woody fuels in logged compared to unlogged stands (Keyser *et al.* 2009; Donato *et al.* 2013; Peterson *et al.* 2015, 2023*a*; Johnson *et al.* 2020). Our simulation results agree with prior studies linking high fuel loads shortly after harvest with higher modeled fire intensities and effects during this time (Johnson *et al.* 2020; Kennedy *et al.* 2024). High fire intensities during this period could also slow forest recovery due to high mortality of young, regenerating trees that are typically less fire resistant. Pile burning or broadcast burning of the fuels produced during post-fire harvest could reduce these initially high fuel loads and further mitigate the potential fire hazard (Dunn and Bailey 2015; Johnson *et al.* 2020; Larson *et al.* 2022). Post-fire logging had little effect on particulate emissions, fire duration and soil heating from simulated wildfires in the first 5 years after initial wildfire, due to negligible differences in large diameter fuels between logged and unlogged stands during this time period.

Beyond the first 5 years, post-fire logging reduced simulated wildfire severity by reducing accumulations of large-diameter woody fuels that contribute to wildfire residence times, soil heating, basal heating of trees and smoke production. Additionally, fine woody fuels declined through decomposition and because few snags remained to deposit new fuels. Declining fine woody fuel loads led to lower simulated wildfire intensities in logged stands, because fine woody fuels exert a stronger influence on fire intensity than do large diameter fuels (DeBano *et al.* 1998; Hyde *et al.* 2011). These results are consistent with other modeling studies showing a reduction of large diameter fuel accumulation and associated fire effects 5 or more years after post-fire logging (Johnson *et al.* 2013, 2020; Kennedy *et al.* 2024).

Managing post-fire fuel dynamics and reburn potential with prescribed fire

Prescribed fire effects differed considerably from post-fire logging effects, as simulated prescribed fire reduced fine woody debris but had relatively little effect on large-diameter fuels. Simulated spring prescribed fires consumed most of the fine woody fuels at many of the sites, but consumption was lower than under simulated summer wildfire conditions. Higher fuel moisture levels in the spring prescribed fire scenario suppressed simulated consumption of the 100- and 1000-h woody fuels and at sites where smaller fuels failed to produce sufficient heat to ignite and sustain combustion. Prescribed burns could be more effective for consuming larger-diameter fuels if conducted when fuel moisture levels are lower, such as in autumn or late spring. We did not simulate autumn prescribed burns partially due to limitations of how rotten fuel moisture is simulated in BURNUP: the model sets rotten fuel moisture at 250% of sound large-diameter fuel moisture (Lutes 2013). While this may be reasonable for prescribed spring burns or early summer wildfires, rotten large-diameter fuel moisture values are likely similar to sound large-diameter fuel moistures for much of the summer wildfire season in many dry coniferous forests. This limitation of the model does, however, suggest that our simulations may underestimate consumption of large rotten fuels, even under spring burning conditions.

Our simulation results suggest that prescribed fire has the potential to mitigate subsequent wildfire effects and that combining prescribed fire with post-fire logging can further reduce the severity of subsequent wildfire. When we simulated a wildfire following a prescribed fire in unlogged stands, fire intensity, emissions, duration and soil heating were all lower than the simulated wildfire with no prior prescribed fire. However, post-fire logging reduced the availability of sound 1000-h fuels and, with fewer fuels to consume, led to lower predicted smoke emissions, maximum fire intensities and fire durations from the simulated wildfire following prescribed fire relative to unlogged stands.

Based on these results, prescribed fire alone could be effective at reducing fine fuel loads and has the potential to mitigate subsequent wildfire severity when large diameter fuels are low. Prescribed fire may also be an appropriate post-fire fuels management approach where management objectives place a high value on retention of snags and large diameter surface woody fuels (Larson *et al.* 2022). Prescribed burning can be conducted when downed logs are moist if maintaining some large diameter fuels is a management objective (Stevens *et al.* 2021; Larson *et al.*

2022). Where pre-fire stand densities were low and large diameter fuels from falling snags are less of a concern, prescribed fire alone may be sufficient to manage post-fire fuel accumulation. Under these circumstances, prescribed fire could be effective at maintaining low levels of fine woody fuels to reduce fire intensity and avoid ignition and consumption of large surface woody fuels. If prescribed fire is the primary management tool, our simulation results suggest that multiple entries may be needed to maintain low fine woody fuel loads and reduce the likelihood of future high severity fires, but this will depend upon pre-fire stand densities and expected rates of fuel accumulation. If sufficient large diameter fuels remain and fine woody fuels are allowed to accumulate, the potential remains for large fuels to ignite with potentially severe fire effects.

Our simulations suggest that post-fire logging could facilitate prescribed fire use and further moderate potential future fire effects, particularly where high loadings of large diameter fuels are a concern. In severely burned forests with high pre-fire tree densities and a long history of fire exclusion, the large pulse of dead trees after high-severity wildfire increases the likelihood of severe reburns (Coppoletta *et al.* 2016; Harvey *et al.* 2016). Post-fire logging in these forests can reduce snag densities, decreasing future fire intensity and severity, as demonstrated here and in prior studies (Johnson *et al.* 2013; Peterson *et al.* 2015; Kennedy *et al.* 2024). By reducing large diameter fuel loads, post-fire logging can reduce wildfire residence times and soil heating (Kennedy *et al.* 2024), which helps to maintain hydrologic function and maintain soil nutrients and microbial communities (Neary *et al.* 1999). Concerns over smoke emissions often limit use of prescribed fire in the Pacific Northwest or near urban centers, where smoke management plans require strict regulation of air quality standards (Schultz *et al.* 2019; Jaffe *et al.* 2020). Under the right circumstances, post-fire logging may mitigate these concerns by reducing smoke emissions or fire intensity of prescribed fires compared to prescribed fires in unlogged stands.

Management implications

Post-fire management through logging, prescribed fire or the combination of both can reduce future fire severity (Johnson *et al.* 2020; Kennedy *et al.* 2024), but the circumstances under which each approach is likely to be most beneficial vary based on factors including landscape context, pre-fire conditions, management objectives, and human safety and social concerns. Our simulations suggest that prescribed fire could be effective at mitigating future fire effects in areas with low loadings of large diameter fuels. Prescribed burning could also be an appropriate post-fire fuels management approach in areas where management objectives prioritize retention of snags and large diameter logs while restoring or transitioning to a surface fire regime (Stevens *et al.* 2021; Larson *et al.* 2022). Additionally, when multiple re-entries with prescribed fire are feasible, prescribed fire could maintain fine fuel loads at low enough levels to prevent ignition of larger fuels.

In severely burned forests with high pre-fire tree densities, our simulations suggest post-fire logging could both reduce subsequent wildfire severity and facilitate the use of prescribed fire in fuels management. Additionally, areas where prescribed fire use is limited by human safety or air quality concerns, such as the wildland–urban interface, could be good candidates for fuels management through post-fire logging. However, post-fire management concerns are not limited only to future wildfire hazards, and post-fire logging can negatively impact wildlife habitat, biogeochemical cycling and increase soil erosion (Leverkus *et al.* 2021). Varying the intensity or spatial pattern of post-fire logging within stands could help balance fuels management for fire hazard reduction with other ecological functions. For example, retaining some snags during post-fire logging, leaving snag species with slower decay rates and managing for a wide range of fuel loads across a landscape can allow for fuels reduction while also retaining habitat for a diversity of wildlife species (Ritchie *et al.* 2013; Ritchie and Knapp 2014; Johnson *et al.* 2020). In our logged stands, mean large diameter fuel loads met established targets (11.1–44.8 Mg ha^{-1}) for balancing fire hazard, wildlife habitat and soil productivity in warm, dry forests (Brown 2003). Because consumption of large diameter fuels was limited in areas with low fine woody fuels, fuel treatments that reduce or create discontinuities in fine woody fuel loads could also allow for retention of some snags and large diameter surface woody fuels as wildlife habitat while also reducing potential future wildfire severity. Potential negative impacts from post-fire logging on soil erosion, productivity and understory vegetation can be mitigated through such steps as limiting construction of new roads, timing harvest for when soils are frozen and more resistant to damage, hand-felling snags when possible and focusing on low to moderate slopes (McIver and McNeil 2006).

The combination of post-fire logging and prescribed burning produced the greatest reductions in surface woody fuels and potential wildfire effects over time in our simulations. A combined approach may therefore be well suited for use in areas where restoration and maintenance of a low severity fire regime is a priority. Combining post-fire logging and prescribed burning led to fuel levels similar to those found after wildfire reburns but produced less soil heating and lower smoke emissions than reburns. These results are consistent with prior modeling studies showing that post-fire logging and prescribed fire together can reduce future fire severity (Johnson *et al.* 2013; Kennedy *et al.* 2024) and align with studies of fuel treatment effectiveness in unburned dry conifer forests, where mechanical thinning treatments combined with prescribed fire tend to be more effective at reducing fuel loads and decreasing future fire severity than prescribed fire on its own (Kalies and Yokom Kent, 2016; Tepley *et al.* 2017).

Limitations

Our results must be interpreted within the context of a simulation experiment and the limitations inherent in the BURNUP model used to model potential fire effects. By necessity, we examined a limited number of fire scenarios: summer wildfire, spring prescribed fire, and a summer wildfire reburn after prescribed fire and made assumptions about fire weather conditions and accumulation of fine fuels in the interval between simulated prescribed fire and the simulated reburn. We based our simulated fire weather scenarios on published information characterizing 97th percentile summer wildfire and typical prescribed burning conditions in dry mixed conifer forests of the Pacific Northwest, but our results should be interpreted in the context of a relative comparison of the potential influence of post-fire management in an experimental comparison between scenarios, rather than precise predictions. One limitation of the BURNUP model is that it simulates fuel consumption and fire effects at a point and assumes continuous fire for the modeled stand. The model does not account for spatial heterogeneity in fuels and ignition of larger fuels is dependent upon heat transfer from smaller fuels. As a result, BURNUP could overestimate consumption of large diameter fuels in stands where spatial discontinuities in smaller fuels could limit ignition of the large fuels. In contrast, the model could underestimate consumption of rotten large-diameter fuels due to the default assumption that rotten fuel moisture is 250% of sound 1000-h fuel moisture, as noted earlier. Additionally, simulated particulate emissions depend upon emissions factors which are estimates with inherent uncertainty (Prichard *et al.* 2020). However, emissions factors affect the magnitude but not the variability in predicted emissions (Kennedy *et al.* 2020), so using the same emissions factors in all three fire scenarios should permit relative comparison of particulate emissions between scenarios. Similarly, fuel SAV values can influence modeled fire behavior and effects. Since we used the same SAV values for all of our fire simulation scenarios, we can make relative comparisons between scenarios but cannot precisely predict fire effects.

Conclusions

Post-fire fuels management need not be a one size fits all proposition. In high density stands with few surviving overstory trees, post-fire logging can be an effective treatment for reducing future woody fuel loads, wildfire intensity and wildfire effects in dry coniferous forests. Prescribed fire can help manage fuel loads in lower density stands or where post-fire logging is either socially unacceptable or does not fit with management objectives but may require multiple entries or some additional mechanical treatments, such as mastication, to maintain acceptable fuel loads over time. Similar to fuel treatments in unburned forests, the combination of mechanical treatments (post-fire logging in this case) and prescribed fire was the most effective at reducing the potential intensity and severity of future wildfires in our simulations. However, post-fire logging and prescribed fire may not be feasible or desirable in all locations. Strategically applied post-fire fuels management through post-fire logging or prescribed fire could help reduce future fire severity and restore low and mixed severity fire regimes in dry coniferous forests. By considering the post-fire conditions and anticipating future fuel accumulation, management activities can vary across landscapes and within stands to reduce fire hazard and threats to human health and communities while maintaining wildlife habitat and ecosystem functions.

Supplementary material

Supplementary material can be accessed from the article page online.

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Conflicts of interest. The authors declare that they have no conflicts of interest.

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